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THERMAL CONDUCTIVITY STANDARD REFERENCE MATERIALS FROM 6 TO 280K: VI. NBS SINTERED TUNGSTEN

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ABSTRACT

Thermal conductivity, electrical resistivity, Lorenz ratio, and thermopower data are reported for two specimens of NBS sintered tungsten for temperatures from 6 to 280 K. Variability of this tungsten was studied by means of electrical resistivity and residual resistivity measurements on 39 specimens. These data indicate a material variability of about ±10% in thermal conductivity at helium temperatures. Above 90 K variation in thermal conductivity is only about ±1%. To reduce the uncertainty caused by specimen variation at low temperatures, characterization by residual electrical resistivity data is described. By this procedure the low temperature uncertainty is reduced to about ±3%.

Key words: Cryogenics, electrical resisitivity, Lorenz ratio, Seebeck effect, standard reference material, thermal conductivity, transport properties, tungsten.

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* This work was carried out at the National Bureau of Standards under the joint sponsorship of the Office of Standard Reference Materials, NBS, Washington, and the Air Force Materials Laboratory, Dayton, Ohio.

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1. Introduction

Design and development engineers in the aerospace industry continue to have urgent need for thermal and mechanical property data for new materials. For most materials, especially new or uncommon alloys, measured values of thermal conductivity are not available and predictions cannot be made with adequate confidence. To help satisfy these needs, we have constructed an apparatus for the simultaneous measurement of thermal conductivity, electrical resistivity and thermopower. Measurements have been conducted on several aerospace alloys, Hust, et al. [1] and several standard reference materials, Hust, et al. [2-4]. We intend to measure several other materials which appear to be useful as standards. For some, material variability may be so great that only standard reference specimens (not standard reference materials) can be used. Standard reference specimens or materials are useful for intercomparison of existing apparatus, for debugging new apparatus, and for calibration of comparative apparatus. The apparent large differences between the results of various investigators for a given material (50% is not unheard of) is evidence of the need for intercomparisons, calibrations, and standardization. The availability of standard reference materials, SRM's, will result in more accurate transport property data for technically important solids.

This paper contains the results of our measurements on the transport properties of a NBS sintered tungsten material obtained from the Office of Standard Reference Materials, National Bureau of Standards. This tungsten has been investigated because of its potential as an extended temperature range SRM. Other tungsten materials have been extensively investigated for use as high temperature thermal conductivity standards by the Advisory Group for Aerospace Research and Development (AGARD), NATO. A sizeable portion of this earlier research was done by the Air Force Materials Laboratory at Dayton, Ohio.

2. Apparatus and Data Analysis

The apparatus is based on the axial one-dimensional heat flow method. The specimen is a cylindrical rod 3.1 mm in diameter and 23 cm long with an electric heater at one end and a temperature-controlled sink at the other. The specimen is surrounded by glass fiber and a temperature-controlled shield. Eight thermocouples are mounted at equally spaced points along the length of the specimen to determine temperature gradients in the range 4 to 300K.

The experimental data are represented by arbitrary functions over the entire range and tables are generated from these functions. The number of terms used to represent each of the data sets is optimized, through the use of orthonormal functions, so that none of the precision of the data is lost by underfitting nor are any unnecessary oscillations introduced by overfitting. A detailed description of this apparatus and the methods of data analysis are given by Hust, et al. [2].

3. Specimen Characterization

Density of the NBS sintered tungsten material is 19.23 g/cm^3 ± 0.05 g/cm^3 and the DPH hardness using a 1 kilogram load is 405 for an annealed specimen and 514 for an unannealed specimen.

A resistivity variability study was conducted on this tungsten to determine if the material variability was small enough for use as a SRM. The results of this study are shown as residual resistivity ratios in table 1. The ratio given is resistivity at 273.15K to resistivity at 4K. A discussion of the connection between electrical resistivity and thermal conductivity variability is given by Hust, et al. [3]. Based on

39 residual resistivity ratio measurements made on these specimens in various states of anneal, it is concluded that the thermal conductivity variability from specimen to specimen in these lots is about 60% at liquid helium temperatures. If one restricts the analysis to the data for the specimens annealed at the highest temperature, 2020° C, the variation is significantly less, ± 10%. This variation is still large for a good low temperature standard. Because of the adjudged value of this material at high temperatures where variability does not pose a problem, we feel that a greater than normally acceptable variability at low temperatures is tolerable. The thermal conductivity variability will be comparable to the electrical resistivity variability. However, the thermal conductivity uncertainty for each specimen need not be this large if one characterizes each specimen by measuring its residual electrical resistivity. The method to obtain corrected thermal conductivities from such an electrical measurement is further explained in the discussion. The method essentially assumes that the Lorenz ratios of the specimens are more nearly identical than the thermal conductivities. This has been shown to be true for many pure metals. See, for example, Hust et al. [5].

4. Results

The transport properties of NBS sintered tungsten specimens in the unannealed and annealed (2020° C) conditions were measured in the thermal conductivity apparatus. These data are presented in tables 2 through 4.

The experimental data were functionally represented with the following equations:

$$\ell n\lambda = \sum_{i=1}^{n} a_i [\ell nT]^{i+1} \quad (1)$$

$$\rho = \sum_{i=1}^{m} b_i [\ell nT]^{i-1} \quad (2)$$

$$S = \sum_{i=1}^{\ell} c_i [\ell nT']^{i}/T'; \quad T' = \frac{T}{10} + 1 \quad (3)$$

where λ = thermal conductivity, ρ = electrical resistivity, S = thermopower, and T = temperature. Temperatures are based on the IPTS-68 scale above 20K and the NBS P2-20 (1965) scale below 20K. The parameters, a_i, b_i, and c_i determined by least squares, are presented in table 5. Further details of this procedure are described by Hust, et al. [1]. The deviations of the experimental data from these equations are given in tables 6 through 11 and in figures 1 through 6. The horizontal bars in figures 2, 3, 5, and 6 indicate the temperature span across the specimen for each run. The "observed" thermal conductivities are computed from the mean temperature gradients indicated by adjacent thermocouples. Calculated values of λ, ρ, S, and L = $\rho\lambda/T$ (Lorenz ratio) for both specimens are presented in tables 12 and 13 and figures 7 through 10.

A detailed error analysis for this system has been presented previously by Hust, et al. [1]. Based on this analysis of systematic and random errors, the uncertainty estimates (with 95% confidence) are as follows:

thermal conductivity:	2.5% at 300K, decreasing as T^4 to 0.70% at 200K, 0.70% from 200K to 50K, increasing inversely with temperature to 1.5% at 4K.
electrical resistivity:	0.5%
thermopower:	0.2 μV.

The thermopower values given here are absolute values although our measurements were carried out with respect to normal silver wire. The absolute thermopowers of normal silver reported by Borelius, et, al. [6] were used to convert the experimental data to the absolute scale.

5. Discussion

The research to establish this tungsten as an SRM is continuing. Because of the time required to complete this program, it is considered desirable to make the current results available for interim use. As pointed out earlier, the variability of this tungsten is greater at low temperatures (below about 90K) than desired. The electrical residual resistivity ratio measurements suggest a variation in thermal conductivity from specimen-to-specimen of as much as ±10% if the specimens are annealed at 2020°C for 1 hour. Other electrical measurements as well as the thermal conductivity measurements show an appreciably larger variation for lower temperature anneals. At the time, 2020°C was the maximum temperature attainable with the existing furnace. It is almost certain that an anneal of 2500°C or above will further reduce the material variability at low temperatures.

Figure 11 shows the thermal conductivity difference between the unanealed and annealed specimens up to a temperature of 90K. Above this temperature, the thermal conductivity differences become progressively smaller. Inadvertently, the unannealed specimen was measured over the total temperature range; the intent was to measure the annealed specimen. This discrepancy is troublesome but not crucial in the analyses of these data.

The intent of the following analysis is to show that the uncertainty (±10%) in low temperature thermal conductivity of the proposed annealed SRM can be considerably reduced on the basis of a simple residual resistivity measurement for each specimen. Consider, first, the definition of

Lorenz ratio, $L = \rho\lambda/T$, and the inverse equation for the computation of thermal conductivity, $\lambda = LT/\rho$. It is clear that the uncertainty in λ now becomes the combined uncertainties of L and ρ at a given temperature. From figure 12 we see that the maximum difference in L for the unannealed and annealed specimens is less than 12% and appears at about 30K. At this temperature, the λ difference is about 35%. Thus, Lorenz ratio variability is about one-third that of thermal conductivity variability for this material.

To determine the uncertainty caused by ρ in the calculation of λ for a particular specimen, we examine the validity of Matthiessen's rule which states that $\rho = \rho_0 + \rho_i$ where ρ_0 is the residual resistivity of the specimen and ρ_i is the intrinsic temperature dependent resistivity of the pure material. It is known that this rule is not satisfied exactly and that a generally small correction term, $\Delta(\rho_0 + \rho_i)$, exists. If this term is sufficiently small, one can reconstruct an adequately accurate ρ vs T curve for a given specimen from knowledge of ρ_i and a measurement of ρ_0 (only one simple measurement). To investigate this possibility, we compute ρ_i from the data for the annealed specimen, neglecting the Δ term. Then we compute Δ from this ρ_i and the data for the unannealed specimen. Figure 13 illustrates the magnitude of Δ with respect to ρ annealed. We see that the variability in ρ_i is one-tenth that in λ, i. e., we can compute ρ for a particular specimen with one tenth the uncertainty which exists in λ due to material variability. It is concluded that the combined uncertainty in L and ρ is at most one third as large as the measured variability in λ. Thus, the $\pm 10\%$ variability in λ can be effectively reduced to about $\pm 3\%$ simply on the basis of a ρ_0 measurement for each specimen. The thermal conductivity, λ, of a standard reference specimen of annealed tungsten can be computed from

$$L = \frac{LT}{\rho} = \frac{LT}{\rho_i + \rho_o}$$

where L and ρ_i are given in table 14 and ρ_o is determined by a liquid helium resistivity measurement. The values of L and ρ_i listed are for tungsten annealed at 2020°C. Smoothing in the vicinity of 90K was necessary because the annealed specimen was only measured up to 90K.

Data and theory supporting the validity of the above method has been summarized by Hust and Sparks [5]. Further improvement in the calculated values of λ by the above method can be obtained through interpolation of the deviations shown in figures 12 and 13. This interpolation would be performed on the basis of the measured ρ_o. The resulting corrections in L and ρ as a function of temperature would probably produce values of λ for each standard reference specimen accurate to better than 1%. Because of the additional complexity of this latter refinement, it is not described in detail. Further information can be obtained from the author.

6. Acknowledgments

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Table 1. Residual resistivity ratio ($\rho_{273\,K}/\rho_{4\,K}$) of NBS sintered tungsten.

Specimen	Heat Treatment	Diameter	RRR
1-1	1200°C, 60 hr	0.625 cm	66.2
1-2	1200°C, 60 hr	0.625 cm	48.8
3-1	1200°C, 60 hr	0.625 cm	69.5
2-2	1200°C, 60 hr	0.625 cm	63.9
6-1	1200°C, 60 hr	0.625 cm	44.2
3-2	1200°C, 60 hr	0.625 cm	65.4
			RRR = 59.6
			σ = 9.2
10-2	1200°C, 60 hr	0.312 cm	56.6
10-7	1200°C, 60 hr	0.312 cm	46.6
14-2	1200°C, 60 hr	0.312 cm	43.5
14-7	1200°C, 60 hr	0.312 cm	45.2
18-2	1200°C, 60 hr	0.312 cm	61.9
18-7	1200°C, 60 hr	0.312 cm	62.5
			RRR = 52.7
			σ = 8.6
1-1	2020°C, 1 hr	0.636 cm	78.0
2-2	2020°C, 1 hr	0.636 cm	76.1
3-1	2020°C, 1 hr	0.636 cm	83.2
4-2	2020°C, 1 hr	0.636 cm	93.5
5-1	2020°C, 1 hr	0.636 cm	82.8
6-1	2020°C, 1 hr	0.636 cm	79.0
6-2 (1)	2020°C, 1 hr	0.636 cm	79.9
6-2 (2)	2020°C, 1 hr	0.636 cm	83.1
6-2 (3)	2020°C, 1 hr	0.636 cm	80.8
6-2 (4)	2020°C, 1 hr	0.636 cm	82.3
6-2 (5)	2020°C, 1 hr	0.636 cm	83.1
			RRR = 82.0
			σ = 4.5

Table 1. Residual resistivity ratio (ρ_{273K}/ρ_{4K}) of NBS sintered tungsten (continued).

Specimen	Heat Treatment	Diameter	RRR
10-2	2020°C, 1 hr	0.318 cm	73.6
11-2	2020°C, 1 hr	0.318 cm	79.0
12-6	2020°C, 1 hr	0.318 cm	80.1
13-1	2020°C, 1 hr	0.318 cm	75.5
14-7	2020°C, 1 hr	0.318 cm	74.9
15-7	2020°C, 1 hr	0.318 cm	81.3
16-4	2020°C, 1 hr	0.318 cm	79.4
17-5 (1)	2020°C, 1 hr	0.318 cm	69.8
17-5 (2)	2020°C, 1 hr	0.318 cm	71.2
17-5 (3)	2020°C, 1 hr	0.318 cm	69.8
17-5 (4)	2020°C, 1 hr	0.318 cm	70.4
17-5 (5)	2020°C, 1 hr	0.318 cm	70.8
17-8	2020°C, 1 hr	0.318 cm	71.5
18-6 (1)	2020°C, 1 hr	0.318 cm	76.8
18-6 (2)	2020°C, 1 hr	0.318 cm	75.1
			RRR = 74.6
			σ = 4.0
14-7	as fabricated	0.318 cm	39.8

Notes Relating to Tables

Tables 2 and 3

The data listed are, in part, card images of experimental data as read into the computer for data processing. These data are not clearly labelled. The following is a line by line explanation of these tables:

1st line - Data identification.

2nd line - Thermocouple emfs (μV).

3rd line - Seebeck emf (μV), specimen current (mA), specimen voltage drop (μV).

4th line - Sample heater voltage (μV), current (mA), platinum resistance thermometer voltage (μV), platinum resistance thermometer current (mA), cryogenic bath pressure (mm of Hg), room temperature (°C), code indicating type of cryogenic bath (1 = liquid helium, 2 = liquid hydrogen, 3 = liquid nitrogen, 4 = dry ice-alcohol, 5 = ice-water).

5th line - Thermocouple temperatures (K).

6th line - Heater power (W), reference temperature (K), specimen resistance (Ω).

Table 4

The data listed are, in part, card images of experimental data as read into the computer for data processing. These data are not labelled clearly. The following is a line by line explanation of these tables:

1st line - Data identification.

2nd line - Platinum resistance thermometer voltage (μV) cryogenic bath pressure (mm of Hg), room temperature (°C), platinum resistance thermometer current (mA), code indicating type of cryogenic bath (1 = liquid helium, 2 = liquid hydrogen, 3 = liquid nitrogen, 4 = dry ice-alcohol, 5 = ice-water), specimen current (mA), specimen voltage (μV), mean emf of eight thermocouples (μV).

3rd line - Reference temperature (K), specimen resistance (Ω), specimen temperature (K).

<u>Tables 6 through 11</u>

These data are semi-processed computer output. Temperature is Kelvin, thermal conductivity is in $Wm^{-1}\ K^{-1}$, electrical resistance is in ohms, and thermovoltage is in μV.

Table 2 (continued)

```
THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN              1MAY73 1530  8
  380.50   501.10   640.80   799.30   976.20  1164.60  1367.00  1577.80
  -273.59    200.00     29.59
  8106750   84.2000    234.55       2.0      654.0      22.0       2.0
THERMOCOUPLE TEMPERATURES
  42.773   49.948   58.089   67.116   76.967   87.199   97.941  108.915
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 6.8259-001             20.224               1.4795-004
--------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN              1MAY73 1745 8A
  326.56   404.78   492.07   588.20   694.65   808.63   933.13  1064.00
  -161.91    200.00     18.43
  6832000   71.0000    233.55       2.0      654.0      22.0       2.0
THERMOCOUPLE TEMPERATURES
  39.511   44.209   49.386   55.011   61.161   67.623   74.558   81.744
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 4.8507-001             20.197               9.2150-005
--------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN              2MAY73 1200  9
   20.31    23.19    26.27    29.30    31.83    34.75    37.58    40.05
    -0.71    300.00      8.34
   869485    9.0500     35.07       2.0      654.0      22.0       1.0
THERMOCOUPLE TEMPERATURES
   5.516    5.740    5.958    6.165    6.358    6.557    6.742    6.927
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 7.8688-003              4.055               2.7800-005
--------------------------------------------------------------
HERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN               2MAY73 1330  10
   45.82    52.01    58.28    64.39    69.83    75.52    81.05    86.10
    -1.79    300.00      8.35
  1387870   14.4500     -0.00      -0.0      655.0      22.0       1.0
THERMOCOUPLE TEMPERATURES
   7.297    7.723    8.131    8.519    8.882    9.238    9.577    9.906
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 2.0055-002              4.056               2.7833-005
--------------------------------------------------------------
```

Table 2 (continued)

```
HERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN             2MAY73 1445  11
   99.06   112.40   125.50   138.00   149.35   160.73   171.74   182.05
    -4.09   300.00     8.41
  2336500  24.3300    -0.00      -0.0     655.0     22.0       1.0
THERMOCOUPLE TEMPERATURES
  10.686   11.509   12.293   13.030   13.714   14.379   15.016   15.631
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 5.6847-002             4.056              2.8033-005
---------------------------------------------------------------
HERMAL CONDUCTIVITY DATA FOR NDS SINTERED TUNGSTEN             2MAY73 1600  12
  209.80   235.35   260.27   284.20   306.35   328.47   350.27   371.47
    -0.96   300.00     8.81
  3891700  40.5000    -0.00      -0.0     655.0     22.0       1.0
THERMOCOUPLE TEMPERATURES
  17.227   18.721   20.164   21.547   22.850   24.138   25.407   26.667
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.5761-001             4.056              2.9367-005
---------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR NDS SINTERED TUNGSTEN            4MAY73 2150 14
   82.97   138.20   193.91   249.57   305.54   361.34   417.71   474.14
   -42.94   200.00   156.39
  3761000  39.0000  34397.10      2.0     630.0     22.0       4.0
THERMOCOUPLE TEMPERATURES
 196.523  199.094  201.682  204.262  206.853  209.431  212.031  214.629
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.4668-001           192.653              7.8195-004
---------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR NDS SINTERED TUNGSTEN            5MAY73 1340 15
  168.79   279.38   391.39   503.56   616.85   730.12   844.95   960.27
   -75.31   200.00   169.32
  5310000  55.0700  34399.00      2.0      -0.0     -0.0       4.0
THERMOCOUPLE TEMPERATURES
 200.524  205.652  210.826  215.990  221.189  226.370  231.608  236.854
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 2.9242-001           192.662              8.4660-004
---------------------------------------------------------------
```

Table 2 (continued)

```
THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN             5MAY73 2000 16
  593.64   748.96   907.25  1065.89  1225.99  1386.59  1549.67  1713.57
   -70.49    100.00     99.09
  6220000   64.4500  34837.00       2.0       -0.0       -0.0       4.0
THERMOCOUPLE TEMPERATURES
 222.187  229.284  236.490  243.686  250.925  258.163  265.493  272.844
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 4.0088-001            194.762              9.9090-004
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN             6MAY73 0040 17
 1082.97  1261.63  1444.53  1627.65  1812.20  1997.47  2185.83  2374.98
   -41.70    100.00    112.81
  6591000   68.3000  35113.50       2.0       -0.0       -0.0       4.0
THERMOCOUPLE TEMPERATURES
 245.748  253.817  262.049  270.268  278.537  286.808  295.218  303.663
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 4.5017-001            196.090              1.1281-003
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN             9MAY73 1800 18
  107.86   179.43   252.30   325.09   398.24   471.50   545.52   619.72
   -16.28    100.00    113.27
  4149550   43.0000  48122.00       2.0       -0.0       -0.0       4.0
THERMOCOUPLE TEMPERATURES
 264.116  267.329  270.598  273.861  277.141  280.412  283.716  287.029
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.7843-001            259.269              1.1327-003
------------------------------------------------------------
```

Table 3. Basic semi-processed temperature gradient data for NBS sintered tungsten (annealed)

```
NO. OF GRADIENT AND ISOTHERMAL RUNS NBS SINTERED TUNGSTEN     ANNEAL
        9          0          8
THERMOCOUPLE POSITIONS AND AVERAGE DIAMETERS (CM)
  0.00000   2.54076   5.08000   7.61924  10.16025  12.70000  15.23949  17.77975
  0.31750   0.31750   0.31750   0.31750   0.31750   0.31750   0.31750
------------------------------------------------------------

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN    ANNEAL  16MAY73 1115   1
   64.26    73.34    82.77    92.30   101.29   110.67   120.18   129.41
   -2.44   300.00     5.26
 3218300  33.5000   223.10      2.0     653.7     23.5      2.0
THERMOCOUPLE TEMPERATURES
  23.636   24.178   24.726   25.279   25.818   26.367   26.919   27.476
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.0781-001           19.919              1.7533-005
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN    ANNEAL  16MAY73 1300   2
  118.80   136.85   155.54   174.97   194.07   214.25   235.07   256.32
   -2.41   300.00     6.11
 4476000  46.5700   224.97      2.0     653.7     23.5      2.0
THERMOCOUPLE TEMPERATURES
  26.886   27.962   29.064   30.211   31.358   32.557   33.793   35.078
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 2.0845-001           19.970              2.0367-005
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN    ANNEAL  16MAY73 1430   3
  191.32   226.74   265.31   306.76   351.14   399.50   452.94   510.80
  -32.95   200.00     6.21
 5962150  62.0000   227.10      2.0     654.7     24.0      2.0
THERMOCOUPLE TEMPERATURES
  31.239   33.363   35.668   38.148   40.824   43.717   46.891   50.324
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 3.6965-001           20.027              3.1050-005
------------------------------------------------------------
```

Table 3 (continued)

```
THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN    ANNEAL  16MAY73 1600   4
  322.12   393.60   475.99   571.16   679.39   798.60   931.17  1073.20
  -144.72    200.00     15.50
  7352200   76.4000    231.00       2.0     654.7      24.0       2.0
THERMOCOUPLE TEMPERATURES
  39.175   43.472   48.368   53.951   60.221   66.994   74.386   82.181
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 5.6171-001             20.130              7.7500-005
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN    ANNEAL  16MAY73 1705   5
  366.40   460.16   571.74   701.60   850.40  1011.54  1188.90  1375.18
  -209.28    200.00     22.00
  8019150   83.3000    232.35       2.0     654.7      24.0       2.0
THERMOCOUPLE TEMPERATURES
  41.869   47.470   54.027   61.517   69.938   78.848   88.442   98.330
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 6.6800-001             20.166              1.1000-004
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN    ANNEAL  18MAY73 1500   6
   28.33    30.55    33.15    35.67    37.64    40.16    42.49    44.55
    -1.23    400.00      5.81
  1133620   11.8000     -0.00      -0.0     655.0      24.5       1.0
THERMOCOUPLE TEMPERATURES
   6.094    6.265    6.444    6.610    6.761    6.929    7.077    7.233
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.3377-002              4.056              1.4525-005
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN    ANNEAL  18MAY73 1540   7
   57.03    61.99    67.17    72.29    76.65    81.60    86.23    90.57
    -3.06    400.00      5.84
  1786370   18.6000     -0.00      -0.0     655.0      24.5       1.0
THERMOCOUPLE TEMPERATURES
   8.039    8.374    8.705    9.023    9.313    9.620    9.899   10.183
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 3.3226-002              4.056              1.4600-005
------------------------------------------------------------
```

Table 3 (continued)

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THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN    ANNEAL  18MAY73 1625   8
  112.51   122.86   133.31   143.52   152.65   162.23   171.42   180.16
    -7.02    400.00      5.94
  2881270   30.0000     -0.00      -0.0     655.0      24.5       1.0
THERMOCOUPLE TEMPERATURES
  11.503   12.138   12.758   13.356   13.908   14.467   14.997   15.521
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 8.6438-002              4.056               1.4850-005
----------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN    ANNEAL  18MAY73 1710   9
  232.39   253.61   275.04   296.19   316.02   336.55   357.10   377.50
    -8.78    400.00      6.59
  4775870   49.7000     -0.00      -0.0     655.0      24.5       1.0
THERMOCOUPLE TEMPERATURES
  18.537   19.780   21.022   22.245   23.414   24.611   25.808   27.022
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 2.3736-001              4.056               1.6475-005
----------------------------------------------------------------
```

Table 4. Basic semi-processed isothermal electrical resistivity data for NBS sintered tungsten (unannealed)

```
ISOTHERMAL RESISTIVITY DATA FOR NBS SINTERED TUNGSTEN          2MAY73 1720 13
   35.07   655.00    22.00      2.00      1.00   300.00     8.33     2.06
REFERENCE TEMPERATURE   SPECIMEN RESISTANCE   SPECIMEN TEMPERATURE
       4.056                2.7767-005                4.222
----------------------------------------------------------------
```

Table 5. Parameters in equations 1, 2, and 3 for NBS sintered tungsten.

Unannealed Specimen

THERMAL CONDUCTIVITY	ELECTRICAL RESISTIVITY	THERMOPOWER
1.23083187+002	2.32248252-007	-4.77902140+003
-3.58896755+002	-6.90059760-007	3.74959331+004
4.76863807+002	8.74523656-007	-1.22859131+005
-3.71460419+002	-6.13855629-007	2.21164325+005
1.86515932+002	2.60856484-007	-2.43908435+005
-6.29083223+001	-6.86620382-008	1.73778224+005
1.44225570+001	1.09229515-008	-8.17454896+004
-2.21990545+000	-9.59844355-010	2.52569176+004
2.19723698-001	3.57364089-011	-4.93402176+003
-1.26431486-002		5.52827982+002
3.21572593-004		-2.70746565+001

Annealed Specimen

THERMAL CONDUCTIVITY	ELECTRICAL RESISTIVITY	THERMOPOWER
7.82605854+001	-2.30392836-008	5.55599828+002
-1.96102930+002	4.89385144-008	-2.24304536+003
2.24227329+002	-4.00878173-008	2.86171709+003
-1.47464497+002	1.62832450-008	-1.46600982+003
6.02616459+001	-3.28337817-009	2.54315461+002
-1.55810593+001	2.63473568-010	1.73778224+005
2.48203550+000	1.09229515-008	-8.17454896+004
-2.22430802-001	-9.59844355-010	2.52569176+004
8.58323382-003	3.57364089-011	-4.93402176+003
-1.26431486-002		5.52827982+002
3.21572593-004		-2.70746565+001

Table 6. Thermal conductivity deviations for NBS sintered tungsten (unannealed)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN 26APR73 1050 1

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
84.998	2.544	2.09+002	2.09+002	0.2
87.562	2.584	2.06+002	2.07+002	-0.5
90.150	2.593	2.05+002	2.05+002	-0.0
92.755	2.615	2.04+002	2.04+002	-0.1
95.370	2.616	2.03+002	2.02+002	0.4
98.002	2.647	2.01+002	2.01+002	-0.2
100.655	2.659	2.00+002	2.00+002	-0.0

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN 26 APR73 1720 2

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
88.552	5.734	2.07+002	2.06+002	0.3
94.348	5.858	2.02+002	2.03+002	-0.3
100.234	5.915	2.00+002	2.00+002	-0.0
106.191	5.999	1.98+002	1.98+002	-0.4
112.193	6.004	1.97+002	1.97+002	0.3
118.243	6.098	1.94+002	1.95+002	-0.6
124.354	6.124	1.94+002	1.94+002	-0.2

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN 26APR73 2140 3

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
103.148	11.087	2.00+002	1.99+002	0.2
114.362	11.341	1.95+002	1.96+002	-0.5
125.758	11.452	1.93+002	1.94+002	-0.2
137.292	11.616	1.91+002	1.92+002	-0.4
148.913	11.625	1.90+002	1.89+002	0.5
160.634	11.818	1.87+002	1.88+002	-0.2
172.482	11.878	1.86+002	1.86+002	0.3

Table 6 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN 26APR73 2330 4

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
151.846	10.851	1.90+002	1.89+002	0.3
162.787	11.032	1.86+002	1.87+002	-0.5
173.823	11.041	1.86+002	1.86+002	0.3
184.908	11.127	1.85+002	1.84+002	0.3
196.043	11.145	1.84+002	1.83+002	0.7
207.279	11.326	1.81+002	1.82+002	-0.3
218.633	11.383	1.81+002	1.81+002	-0.1

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN 1 MAY 73 1045 5

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
24.355	0.513	3.91+002	3.97+002	-1.5
24.861	0.499	4.02+002	3.99+002	0.8
25.363	0.506	3.96+002	4.00+002	-1.0
25.866	0.499	4.02+002	4.01+002	0.1
26.363	0.495	4.05+002	4.02+002	0.8
26.859	0.497	4.03+002	4.02+002	0.2
27.358	0.501	4.01+002	4.02+002	-0.4

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN 1MAY73 1200 6

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
27.269	1.201	4.01+002	4.02+002	-0.3
28.464	1.190	4.04+002	4.01+002	0.8
29.665	1.211	3.97+002	3.99+002	-0.3
30.875	1.208	3.98+002	3.95+002	0.9
32.088	1.218	3.95+002	3.90+002	1.4
33.321	1.249	3.85+002	3.84+002	0.4
34.581	1.271	3.79+002	3.77+002	0.5

Table 6 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN 1MAY73 1330 7

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
31.987	2.512	3.92+002	3.90+002	0.6
34.547	2.607	3.78+002	3.77+002	0.2
37.215	2.731	3.61+002	3.61+002	-0.1
40.022	2.882	3.42+002	3.44+002	-0.5
42.966	3.007	3.28+002	3.26+002	0.6
46.079	3.220	3.06+002	3.08+002	-0.6
49.385	3.392	2.91+002	2.91+002	-0.0

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN 1MAY73 1530 8

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
46.360	7.175	3.05+002	3.06+002	-0.3
54.019	8.141	2.69+002	2.70+002	-0.5
62.602	9.027	2.43+002	2.42+002	0.1
72.041	9.851	2.22+002	2.23+002	-0.4
82.083	10.232	2.14+002	2.11+002	1.4
92.570	10.742	2.04+002	2.04+002	-0.0
103.428	10.974	2.00+002	1.99+002	0.2

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN 1MAY73 1745 8A

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
41.860	4.698	3.32+002	3.32+002	-0.2
46.797	5.177	3.01+002	3.04+002	-1.1
52.198	5.625	2.77+002	2.78+002	-0.4
58.086	6.150	2.53+002	2.56+002	-0.9
64.392	6.462	2.41+002	2.38+002	1.2
71.091	6.934	2.24+002	2.25+002	-0.2
78.151	7.186	2.17+002	2.15+002	0.8

Table 6 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN 2MAY73 1200 9

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
5.628	0.224	1.13+002	1.13+002	-0.6
5.849	0.218	1.16+002	1.18+002	-1.4
6.062	0.206	1.22+002	1.22+002	0.6
6.262	0.194	1.30+002	1.26+002	3.6
6.457	0.198	1.27+002	1.30+002	-1.8
6.649	0.185	1.36+002	1.34+002	1.8
6.834	0.185	1.36+002	1.38+002	-0.9

HERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN 2MAY73 1330 10

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
7.510	0.426	1.51+002	1.52+002	-0.2
7.927	0.408	1.58+002	1.60+002	-1.6
8.325	0.388	1.66+002	1.68+002	-1.2
8.701	0.363	1.77+002	1.75+002	1.2
9.060	0.356	1.81+002	1.82+002	-0.9
9.407	0.339	1.90+002	1.89+002	0.6
9.742	0.330	1.95+002	1.95+002	0.1

HERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN 2MAY73 1445 11

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
11.098	0.823	2.22+002	2.20+002	0.7
11.901	0.784	2.33+002	2.35+002	-0.9
12.662	0.737	2.48+002	2.49+002	-0.4
13.372	0.684	2.67+002	2.61+002	2.0
14.047	0.665	2.74+002	2.73+002	0.3
14.697	0.636	2.86+002	2.85+002	0.5
15.323	0.616	2.96+002	2.96+002	0.2

Table 6 (continued)

HERMAL CONDUCTIVITY DATA FOR NDS SINTERED TUNGSTEN 2MAY73 1600 12

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
17.974	1.494	3.39+002	3.38+002	0.3
19.443	1.443	3.50+002	3.57+002	-2.0
20.856	1.383	3.66+002	3.73+002	-2.0
22.199	1.303	3.88+002	3.85+002	1.0
23.494	1.288	3.93+002	3.93+002	-0.1
24.772	1.269	3.98+002	3.99+002	-0.0
26.037	1.260	4.02+002	4.01+002	0.0

THERMAL CONDUCTIVITY DATA FOR NDS SINTERED TUNGSTEN 4MAY73 2150 14

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
197.809	2.570	1.83+002	1.83+002	0.2
200.388	2.588	1.82+002	1.83+002	-0.4
202.972	2.581	1.82+002	1.82+002	0.0
205.558	2.590	1.82+002	1.82+002	-0.2
208.142	2.578	1.83+002	1.82+002	0.3
210.731	2.600	1.81+002	1.82+002	-0.4
213.330	2.598	1.81+002	1.81+002	-0.1

THERMAL CONDUCTIVITY DATA FOR NDS SINTERED TUNGSTEN 5MAY73 1340 15

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
203.088	5.127	1.83+002	1.82+002	0.4
208.239	5.175	1.81+002	1.82+002	-0.3
213.408	5.164	1.82+002	1.81+002	0.2
218.590	5.198	1.81+002	1.81+002	-0.2
223.779	5.182	1.81+002	1.80+002	0.3
228.989	5.238	1.79+002	1.80+002	-0.5
234.231	5.246	1.79+002	1.79+002	-0.3

Table 6 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN 5MAY73 2000 16

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
225.735	7.097	1.81+002	1.80+002	0.6
232.887	7.206	1.78+002	1.80+002	-0.6
240.088	7.197	1.79+002	1.79+002	-0.1
247.306	7.239	1.78+002	1.78+002	-0.2
254.544	7.238	1.78+002	1.77+002	0.2
261.828	7.329	1.75+002	1.76+002	-0.6
269.169	7.352	1.75+002	1.76+002	-0.3

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN 6MAY73 0040 17

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
249.783	8.069	1.79+002	1.78+002	0.7
257.933	8.232	1.75+002	1.77+002	-0.9
266.159	8.220	1.76+002	1.76+002	-0.1
274.403	8.268	1.75+002	1.75+002	0.0
282.672	8.272	1.75+002	1.74+002	0.6
291.013	8.410	1.72+002	1.72+002	-0.4
299.441	8.445	1.71+002	1.71+002	-0.0

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN 9MAY73 1800 18

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
265.723	3.213	1.78+002	1.76+002	1.3
268.963	3.269	1.75+002	1.76+002	-0.2
272.229	3.263	1.75+002	1.75+002	0.2
275.501	3.280	1.75+002	1.75+002	0.0
278.776	3.271	1.75+002	1.74+002	0.5
282.064	3.305	1.73+002	1.74+002	-0.3
285.373	3.313	1.73+002	1.73+002	-0.2

Table 7. Thermal conductivity deviations for NBS sintered tungsten (annealed)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN ANNEAL 16MAY73 1115 1

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
23.907	0.542	6.38+002	6.39+002	-0.1
24.452	0.548	6.30+002	6.37+002	-1.1
25.003	0.553	6.26+002	6.35+002	-1.6
25.549	0.539	6.42+002	6.32+002	1.5
26.092	0.548	6.31+002	6.29+002	0.3
26.643	0.552	6.26+002	6.24+002	0.3
27.197	0.557	6.21+002	6.19+002	0.2

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN ANNEAL 16MAY73 1300 2

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
27.424	1.077	6.21+002	6.17+002	0.7
28.513	1.102	6.07+002	6.05+002	0.2
29.638	1.146	5.83+002	5.91+002	-1.4
30.784	1.147	5.83+002	5.75+002	1.4
31.958	1.200	5.57+002	5.58+002	-0.1
33.175	1.236	5.41+002	5.39+002	0.3
34.435	1.285	5.21+002	5.20+002	0.1

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN ANNEAL 16MAY73 1430 3

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
32.301	2.124	5.58+002	5.53+002	1.0
34.515	2.304	5.14+002	5.19+002	-0.8
36.908	2.480	4.78+002	4.82+002	-0.9
39.486	2.676	4.43+002	4.45+002	-0.4
42.270	2.892	4.10+002	4.09+002	0.3
45.304	3.174	3.74+002	3.75+002	-0.3
48.607	3.433	3.45+002	3.44+002	0.5

Table 7 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN ANNEAL 16MAY73 1600 4

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
41.324	4.297	4.20+002	4.21+002	-0.3
45.920	4.895	3.68+002	3.68+002	-0.1
51.160	5.584	3.23+002	3.24+002	-0.4
57.086	6.270	2.88+002	2.89+002	-0.4
63.608	6.772	2.66+002	2.63+002	1.1
70.690	7.392	2.44+002	2.45+002	-0.5
78.283	7.795	2.31+002	2.32+002	-0.2

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN ANNEAL 16MAY73 1705 5

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
44.670	5.601	3.83+002	3.81+002	0.4
50.748	6.557	3.27+002	3.27+002	-0.0
57.772	7.490	2.86+002	2.85+002	0.2
65.728	8.421	2.55+002	2.57+002	-0.9
74.393	8.910	2.41+002	2.38+002	1.1
83.645	9.594	2.23+002	2.25+002	-0.6
93.386	9.888	2.17+002	2.16+002	0.2

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN ANNEAL 18MAY73 1500 6

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
6.179	0.171	2.51+002	2.47+002	1.6
6.354	0.179	2.40+002	2.53+002	-5.3
6.527	0.166	2.58+002	2.59+002	-0.3
6.686	0.151	2.84+002	2.64+002	6.8
6.845	0.167	2.56+002	2.70+002	-5.3
7.003	0.149	2.89+002	2.76+002	4.6
7.155	0.155	2.77+002	2.81+002	-1.6

Table 7 (continued)

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN ANNEAL 18MAY73 1540 7

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
8.206	0.336	3.18+002	3.18+002	-0.2
8.540	0.330	3.22+002	3.30+002	-2.3
8.864	0.319	3.35+002	3.41+002	-1.9
9.168	0.290	3.68+002	3.51+002	4.5
9.466	0.306	3.48+002	3.61+002	-3.6
9.759	0.280	3.81+002	3.70+002	2.8
10.041	0.284	3.76+002	3.79+002	-0.9

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN ANNEAL 18MAY73 1625 8

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
11.820	0.635	4.37+002	4.34+002	0.6
12.448	0.621	4.47+002	4.53+002	-1.4
13.057	0.598	4.64+002	4.70+002	-1.5
13.632	0.552	5.03+002	4.87+002	3.2
14.188	0.559	4.96+002	5.02+002	-1.1
14.732	0.530	5.23+002	5.16+002	1.3
15.259	0.524	5.29+002	5.30+002	-0.2

THERMAL CONDUCTIVITY DATA FOR NBS SINTERED TUNGSTEN ANNEAL 18MAY73 1710 9

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
19.158	1.243	6.13+002	6.09+002	0.7
20.401	1.242	6.13+002	6.24+002	-1.8
21.633	1.223	6.22+002	6.34+002	-1.9
22.830	1.170	6.51+002	6.39+002	2.0
24.012	1.196	6.36+002	6.39+002	-0.3
25.209	1.197	6.36+002	6.34+002	0.3
26.415	1.214	6.27+002	6.26+002	0.1

Table 8. Electrical resistivity deviations for NBS sintered tungsten (unannealed)

MEAN TEMPERATURE	TEMPERATURE RANGE	OBSERVED RESISTANCE	CALCULATED RESISTANCE	PERCENT DEVIATION
92.784	18.257	2.268-004	2.262-004	0.30
106.302	41.731	2.925-004	2.919-004	0.20
137.512	80.817	4.465-004	4.469-004	-0.10
185.045	77.905	6.825-004	6.823-004	0.03
25.861	3.509	3.045-005	3.055-005	-0.33
30.895	8.547	3.335-005	3.309-005	0.78
40.314	20.350	4.465-005	4.444-005	0.47
73.300	66.142	1.479-004	1.484-004	-0.33
58.939	42.233	9.215-005	9.263-005	-0.52
6.249	1.411	2.780-005	2.775-005	0.18
8.667	2.609	2.783-005	2.797-005	-0.49
13.300	4.945	2.803-005	2.782-005	0.75
22.111	9.440	2.937-005	2.962-005	-0.88
205.561	18.105	7.820-004	7.829-004	-0.12
218.617	36.330	8.466-004	8.467-004	-0.02
247.365	50.658	9.909-004	9.894-004	0.16
274.485	57.915	1.128-003	1.129-003	-0.05
275.518	22.913	1.133-003	1.133-003	-0.02
4.222	0.000	2.777-005	2.777-005	-0.02

Table 9. Electrical resistivity deviations for NBS sintered tungsten (annealed)

MEAN TEMPERATURE	TEMPERATURE RANGE	OBSERVED RESISTANCE	CALCULATED RESISTANCE	PERCENT DEVIATION
25.549	3.840	1.753-005	1.734-005	1.11
30.847	8.192	2.037-005	2.043-005	-0.33
39.913	19.085	3.105-005	3.124-005	-0.63
58.296	43.006	7.750-005	7.697-005	0.68
67.192	56.461	1.100-004	1.104-004	-0.34
6.678	1.139	1.452-005	1.454-005	-0.08
9.149	2.144	1.460-005	1.456-005	0.30
13.591	4.018	1.485-005	1.491-005	-0.43
22.808	8.485	1.647-005	1.652-005	-0.29

Table 10. Thermovoltage deviations for NBS sintered tungsten (unannealed)

UPPER TEMPERATURE	LOWER TEMPERATURE	OBSERVED THERMOVOLTAGE	CALCULATED THERMOVOLTAGE	DEVIATION
101.984	83.727	-81.09	-81.03	-0.06
127.416	85.685	-179.18	-179.45	0.27
178.421	97.604	-303.90	-303.81	-0.09
224.325	146.420	-217.44	-217.50	0.06
27.608	24.099	-1.53	-1.40	-0.13
35.216	26.669	-10.47	-9.95	-0.52
51.081	30.731	-50.85	-51.05	0.20
108.915	42.773	-273.59	-273.42	-0.17
81.744	39.511	-161.91	-162.03	0.12
6.927	5.516	-0.71	-0.60	-0.11
9.906	7.297	-1.79	-2.00	0.21
15.631	10.686	-4.09	-3.86	-0.23
26.667	17.227	-0.96	-1.25	0.29
214.629	196.523	-42.94	-42.81	-0.13
236.854	200.524	-75.31	-75.29	-0.02
272.844	222.187	-70.49	-70.53	0.04
303.663	245.748	-41.70	-41.81	0.11
287.029	264.116	-16.28	-15.95	-0.33

Table 11. Thermovoltage deviations for NBS sintered tungsten (annealed)

UPPER TEMPERATURE	LOWER TEMPERATURE	OBSERVED THERMOVOLTAGE	CALCULATED THERMOVOLTAGE	DEVIATION
27.476	23.636	-2.44	-2.61	0.17
35.078	26.886	-2.41	-6.47	4.06
50.324	31.239	-32.95	-31.23	-1.72
82.181	39.175	-144.72	-145.25	0.53
98.330	41.869	-209.28	-209.08	-0.20
7.233	6.094	-1.23	-0.74	-0.49
10.183	8.039	-3.06	-3.60	0.54
15.521	11.503	-7.02	-7.31	0.29
27.022	18.537	-8.78	-7.09	-1.69

Table 12. Transport properties of NBS sintered tungsten (unannealed)

Temp (K)	Thermal Conductivity ($Wm^{-1}K^{-1}$)	Electrical Resistivity (n Ω m)	Lorenz Ratio $(V^2/K^2)10^8$	Thermo-power (μV/K)
6	120	1.229	2.47	-0.41
7	141	1.253	2.52	-0.41
8	162	1.252	2.53	-0.63
9	181	1.242	2.50	-0.85
10	200	1.233	2.47	-0.97
12	237	1.229	2.42	-0.88
14	273	1.241	2.42	-0.52
16	307	1.260	2.42	-0.13
18	338	1.280	2.40	0.17
20	364	1.298	2.36	0.31
25	399	1.347	2.15	0.09
30	398	1.439	1.91	-0.59
35	374	1.610	1.72	-1.35
40	344	1.884	1.62	-2.02
45	314	2.268	1.58	-2.56
50	288	2.759	1.59	-2.98
55	266	3.352	1.62	-3.29
60	250	4.036	1.68	-3.52
65	237	4.800	1.75	-3.69
70	227	5.635	1.82	-3.81
75	219	6.528	1.91	-3.89
80	213	7.472	1.99	-3.94
85	209	8.456	2.08	-3.96
90	205	9.475	2.16	-3.96
95	203	10.52	2.24	-3.93
100	200	11.59	2.32	-3.89
110	197	13.77	2.47	-3.76
120	195	15.99	2.60	-3.57
130	193	18.22	2.70	-3.35
140	191	20.46	2.79	-3.12
150	189	22.68	2.86	-2.87
160	188	24.90	2.92	-2.62
170	186	27.10	2.97	-2.37
180	185	29.29	3.01	-2.12
190	184	31.47	3.04	-1.87
200	183	33.64	3.07	-1.61
220	181	37.99	3.12	-1.09
240	179	42.38	3.16	-0.53
260	177	46.85	3.18	0.05
280	174	51.47	3.20	0.65

Table 13. Transport properties of NBS sintered tungsten (annealed)

Temp (K)	Thermal Conductivity ($Wm^{-1}K^{-1}$)	Electrical Resistivity ($n\Omega$ m)	Lorenz Ratio (V^2/K^2)10^8	Thermo-power ($\mu V/K$)
7	275	0.6493	2.56	-0.85
8	311	0.6488	2.52	-1.34
9	345	0.6478	2.49	-1.66
10	378	0.6487	2.45	-1.83
12	440	0.6559	2.40	-1.85
14	497	0.6662	2.36	-1.64
16	548	0.6773	2.32	-1.32
18	590	0.6892	2.26	-1.00
20	620	0.7033	2.18	-0.72
25	635	0.7614	1.93	-0.31
30	586	0.8749	1.71	-0.30
35	511	1.065	1.55	-0.58
40	438	1.342	1.47	-1.04
45	378	1.713	1.44	-1.59
50	332	2.178	1.45	-2.14
55	300	2.738	1.49	-2.66
60	276	3.389	1.56	-3.10
65	259	4.127	1.64	-3.45
70	246	4.950	1.74	-3.71
75	237	5.854	1.85	-3.87
80	229	6.833	1.96	-3.92
85	223	7.885	2.07	-3.89
90	218	9.005	2.19	-3.76

Table 14. Intrinsic resistivity and Lorenz ratio of annealed NBS sintered tungsten.

Temperature (K)	Lorenz Ratio $(V^2/K^2)\,10^8$	Electrical Resistivity $(n\Omega\,m)$
7	2.56	.00
8	2.52	.00
9	2.49	.00
10	2.45	.00
12	2.40	.00
14	2.36	.01
16	2.32	.02
18	2.26	.04
20	2.18	.06
25	1.93	.11
30	1.71	.21
35	1.55	.39
40	1.47	.67
45	1.44	1.05
50	1.45	1.52
55	1.49	2.10
60	1.56	2.77
65	1.64	3.52
70	1.74	4.35
75	1.85	5.25

Temperature (K)	Lorenz Ratio $(V^2/K^2)\,10^8$	Electrical Resistivity $(n\Omega\,m)$
80	1.96	6.21
85	2.07	7.23
90	2.18	8.24
95	2.28	9.28
100	2.37	10.35
110	2.51	12.53
120	2.61	14.75
130	2.70	16.98
140	2.79	19.22
150	2.86	21.44
160	2.92	23.66
170	2.97	25.86
180	3.01	28.05
190	3.04	30.23
200	3.07	32.40
220	3.12	36.75
240	3.16	41.14
260	3.18	45.61
280	3.20	50.23

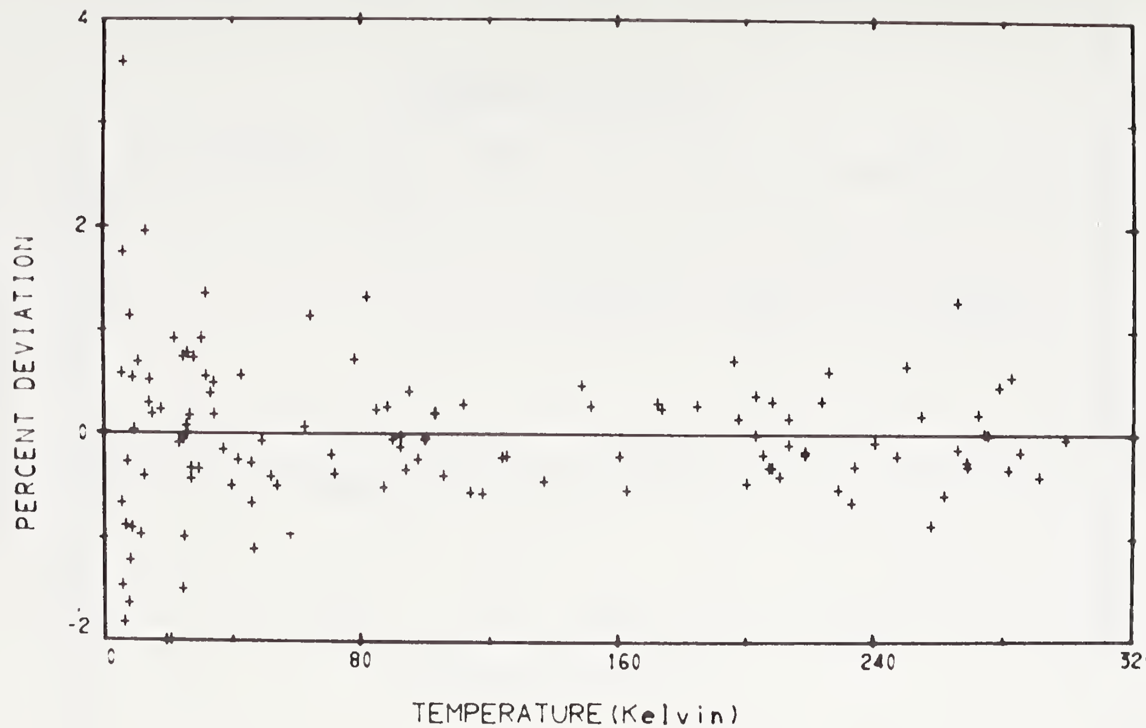

Figure 1. Thermal conductivity deviations for NBS sintered tungsten (unannealed)

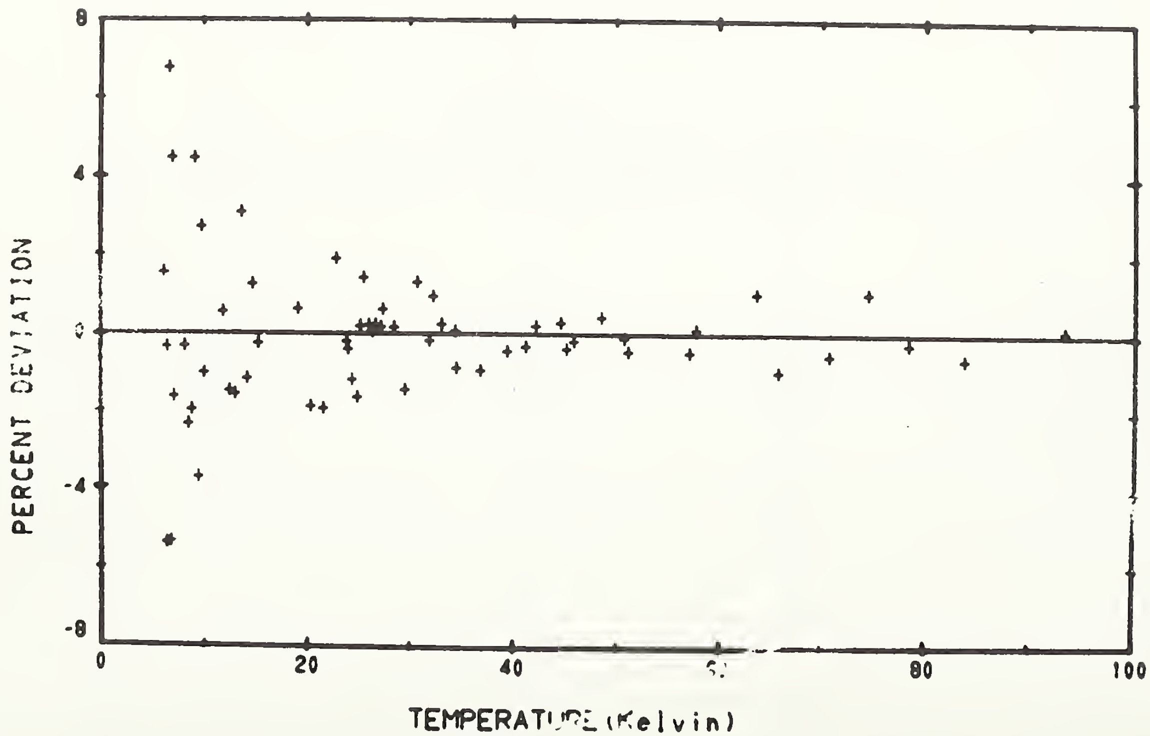

Figure 2. Thermal conductivity deviations for NBS sintered tungsten (annealed)

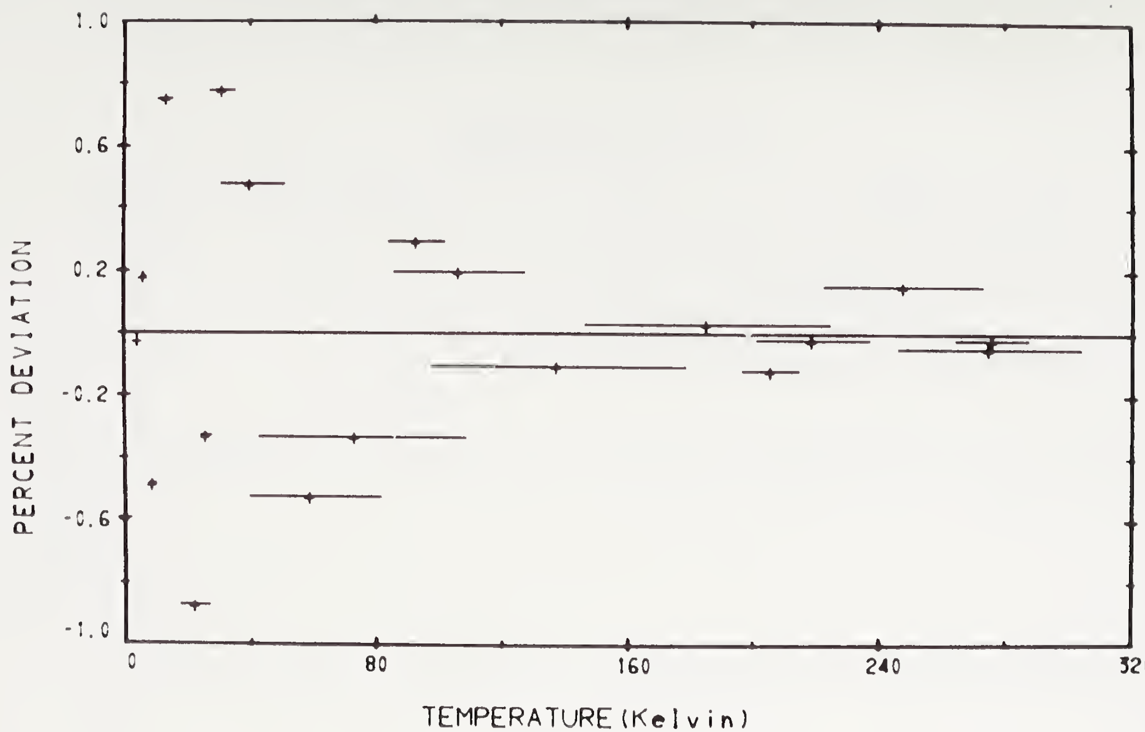

Figure 3. Electrical resistivity deviations for NBS sintered tungsten (unannealed)

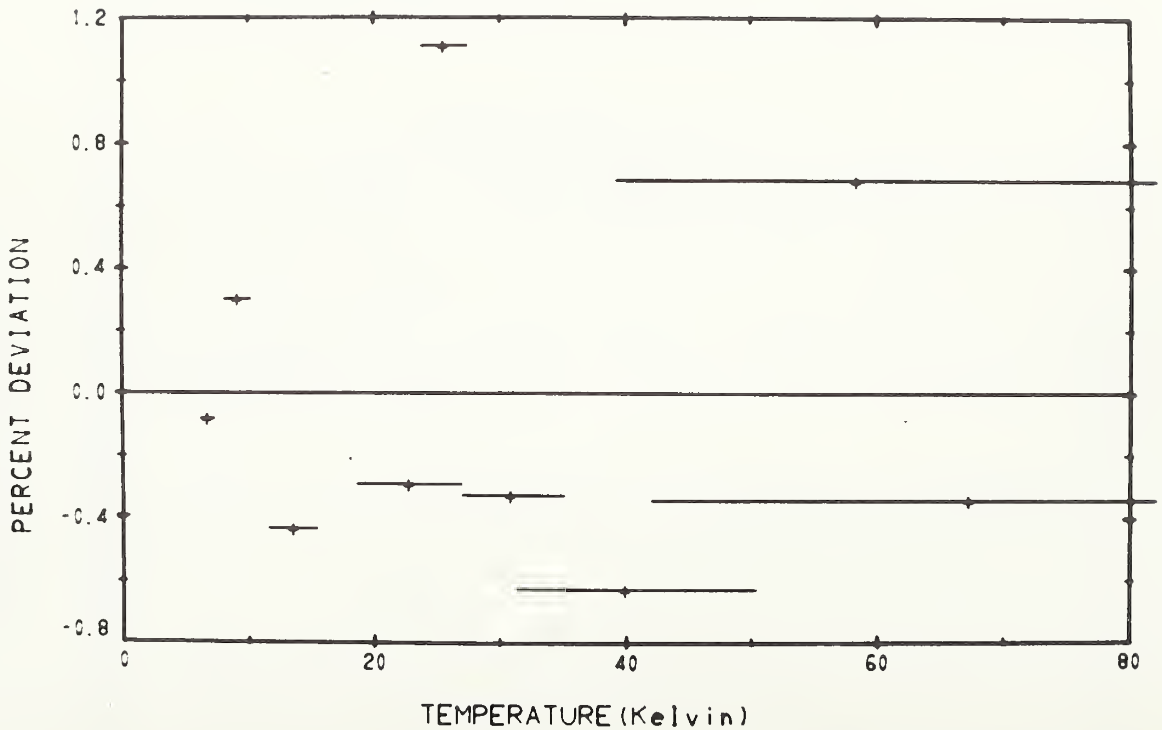

Figure 4. Electrical resistivity deviations for NBS sintered tungsten (annealed)

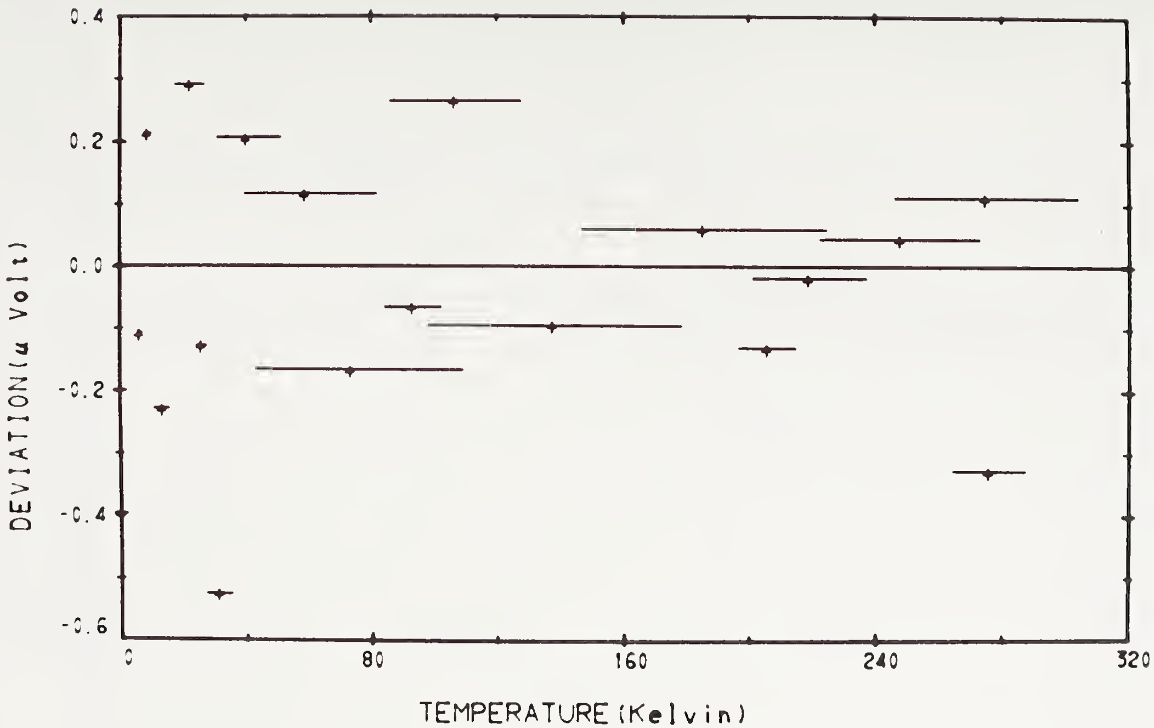

Figure 5. Thermovoltage deviations for NBS sintered tungsten (unannealed)

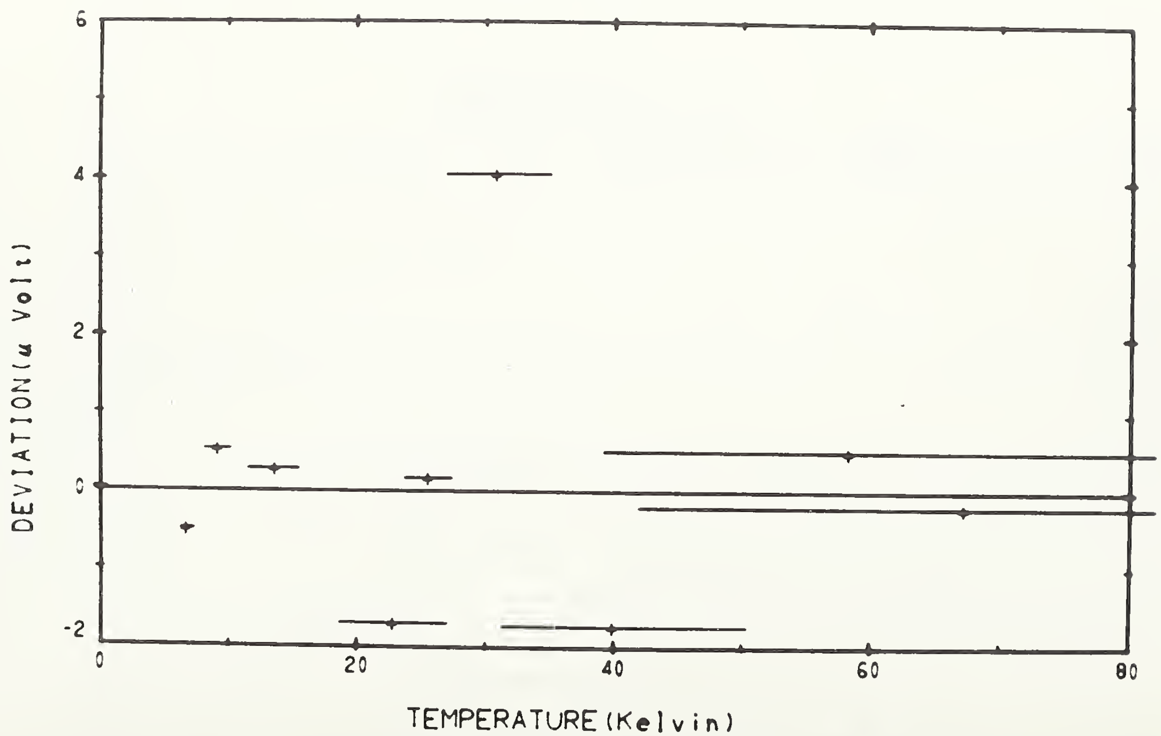

Figure 6. Thermovoltage deviations for NBS sintered tungsten (annealed)

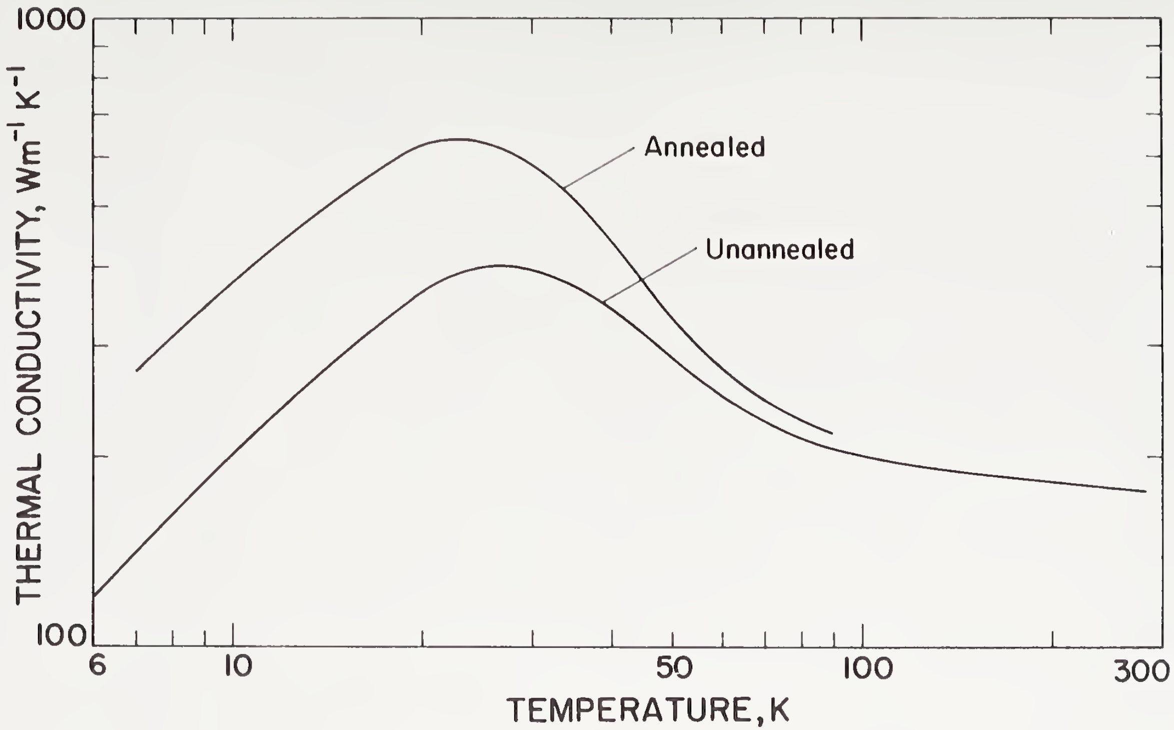

Figure 7. Thermal conductivity of NBS sintered tungsten.

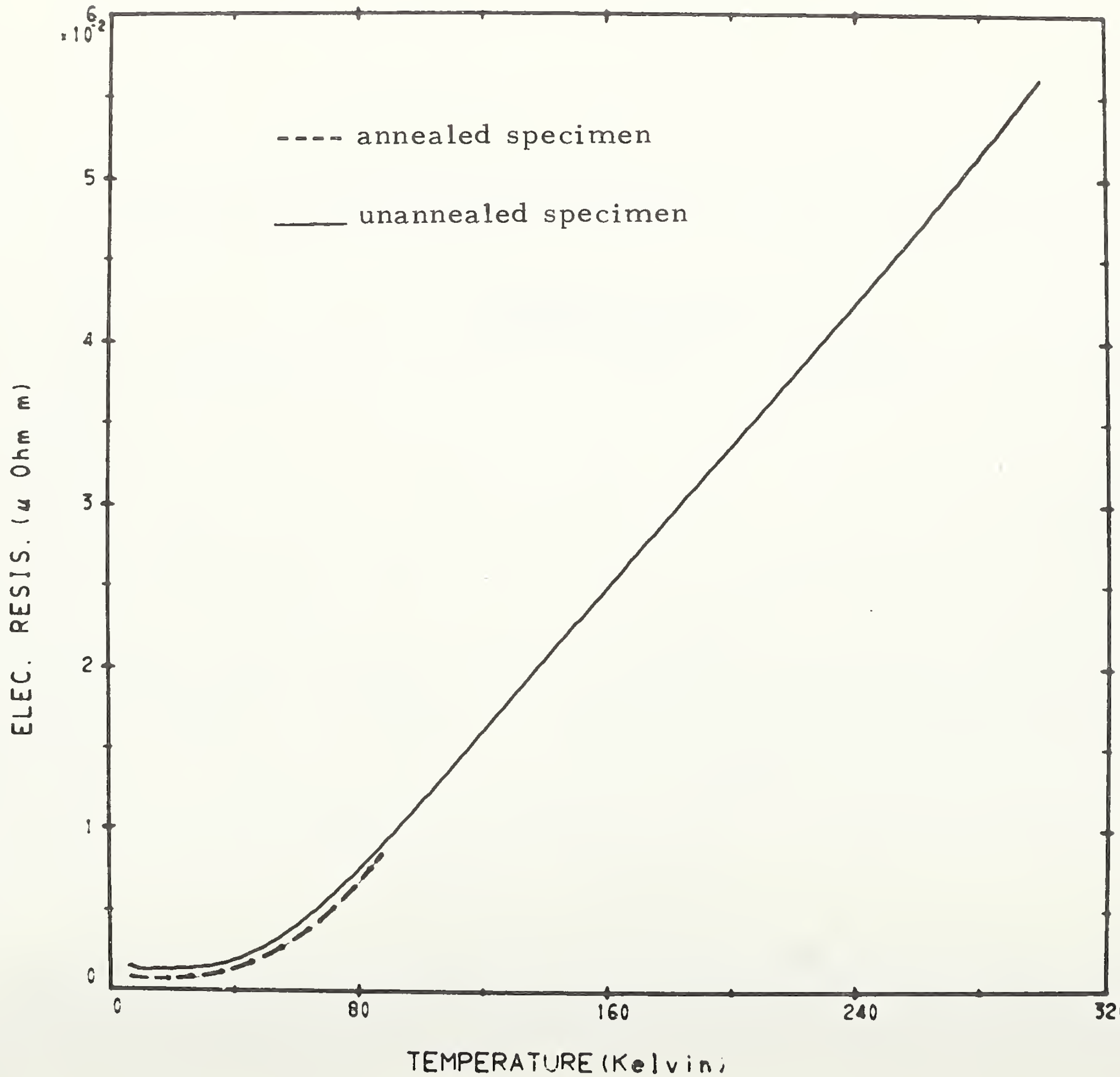

Figure 8. Electrical resistivity of NBS sintered tungsten.

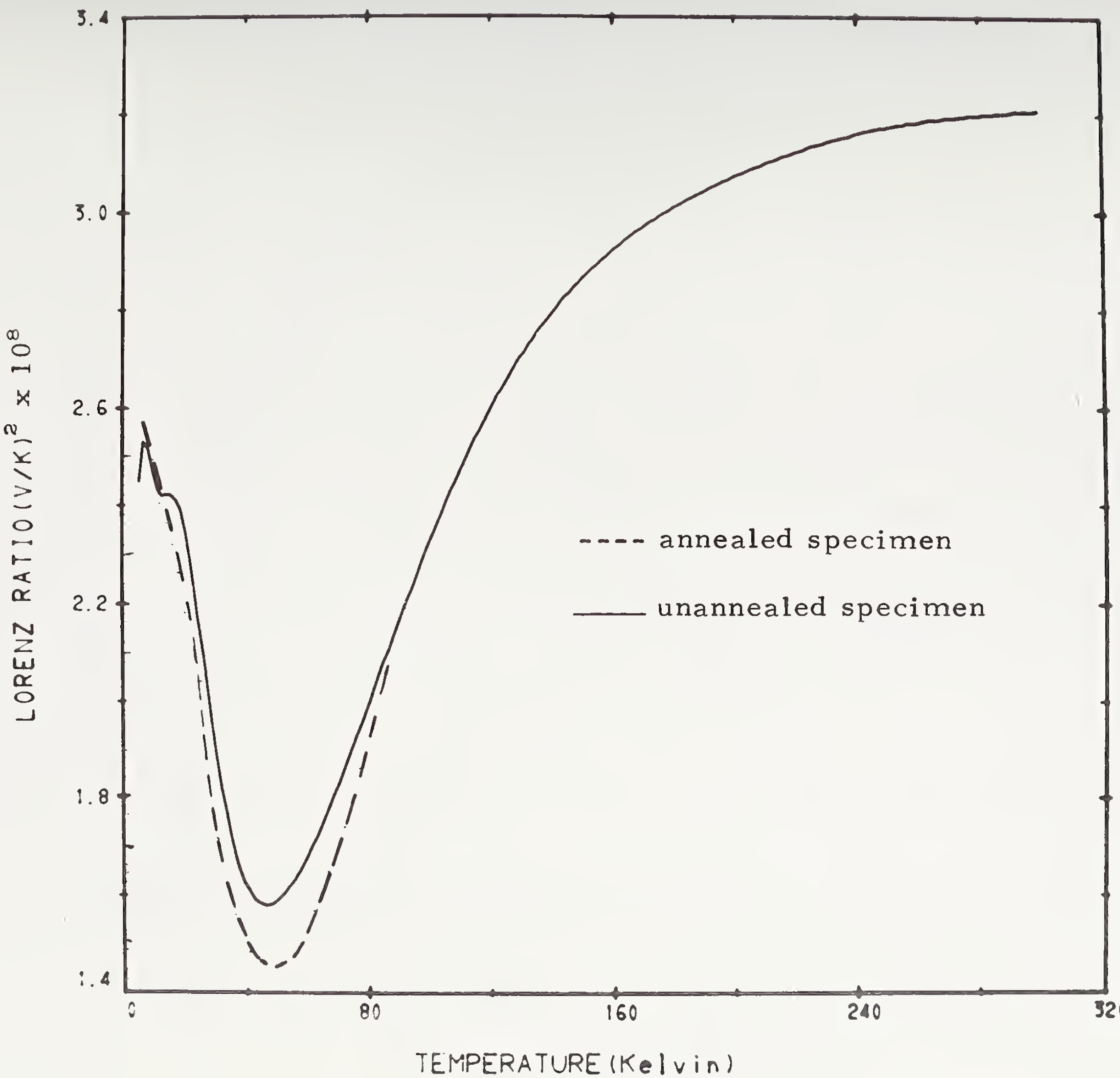

Figure 9. Lorenz ratio of NBS sintered tungsten.

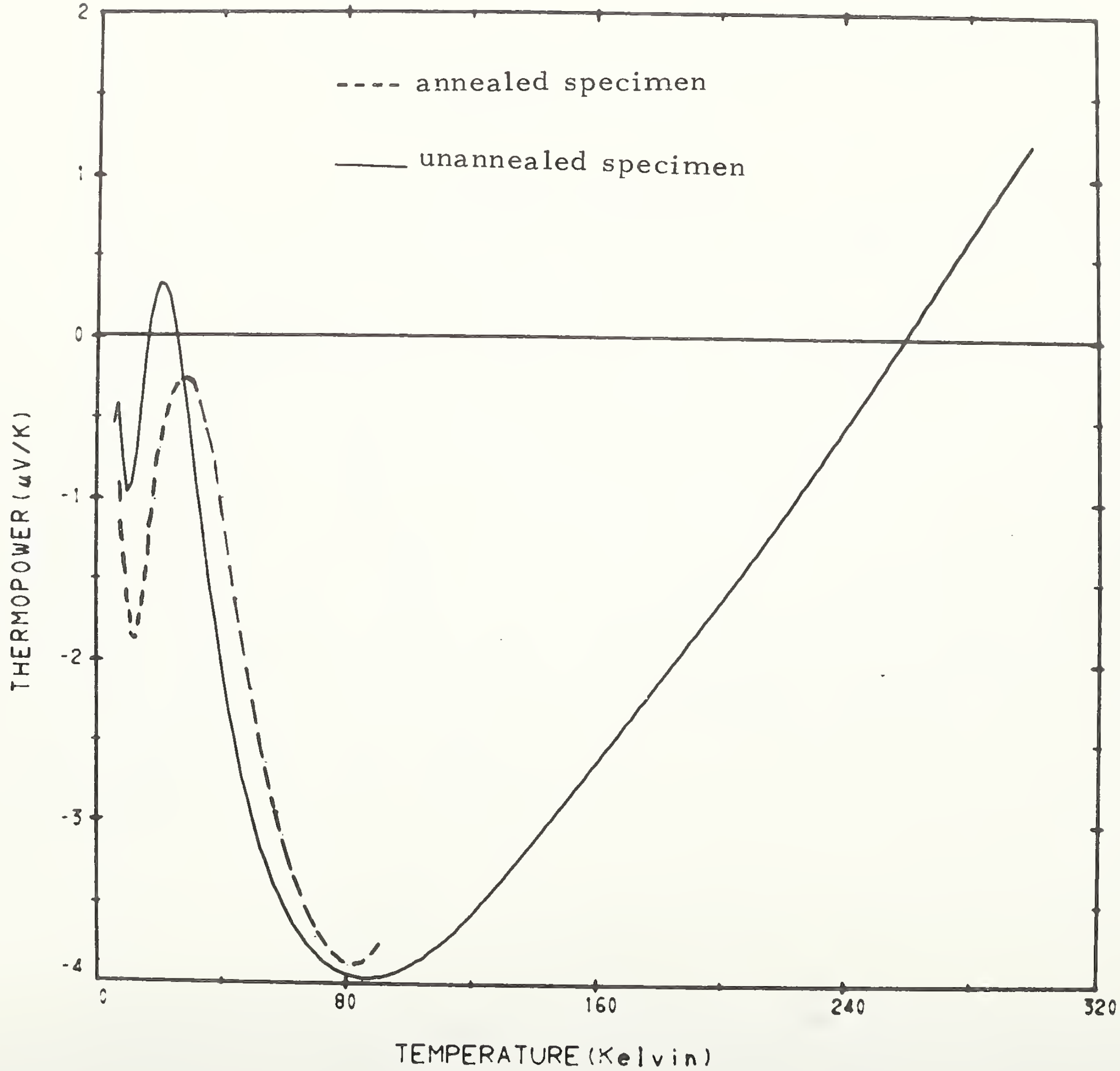

Figure 10. Thermopower of NBS sintered tungsten.

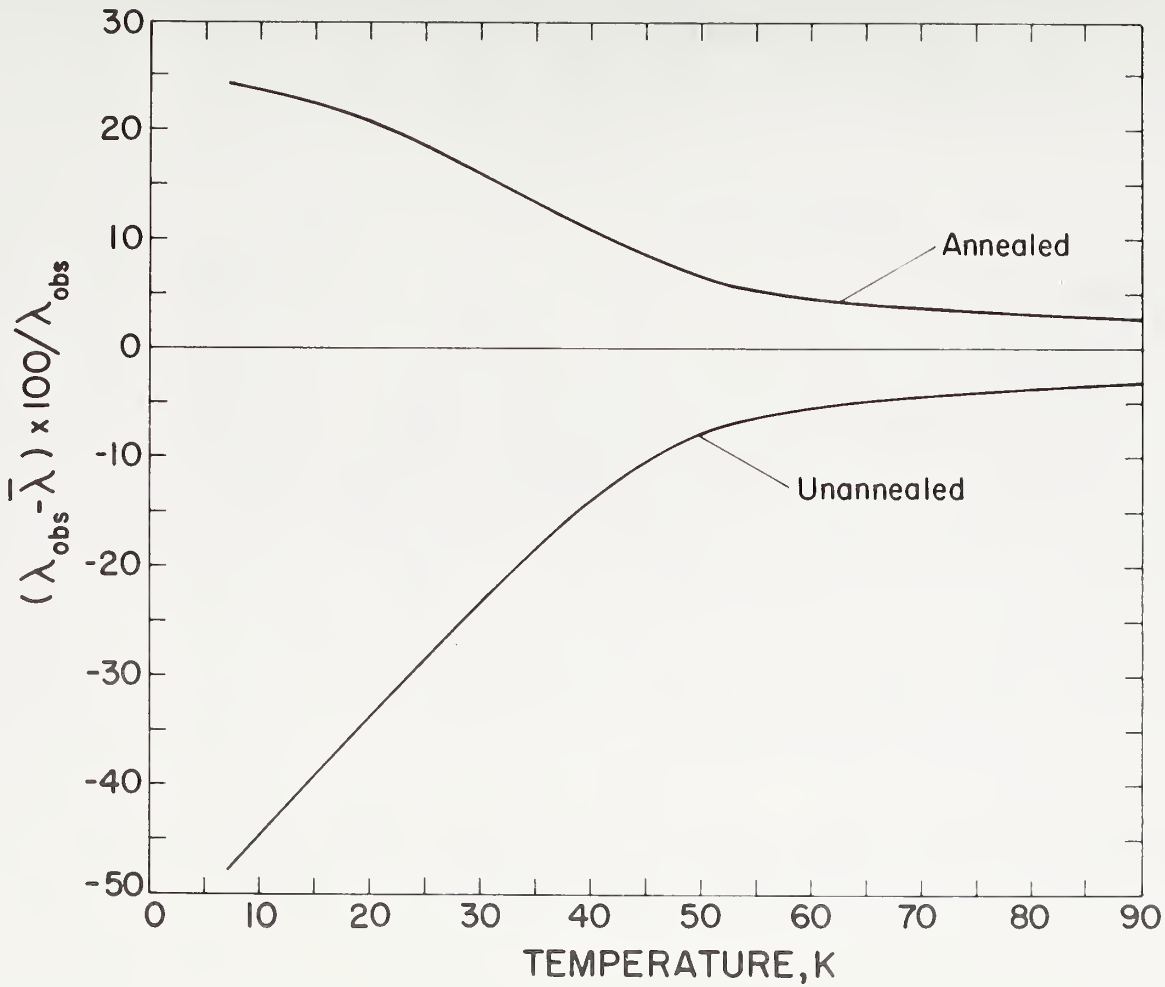

Figure 11. Thermal conductivity differences between annealed and unannealed specimens

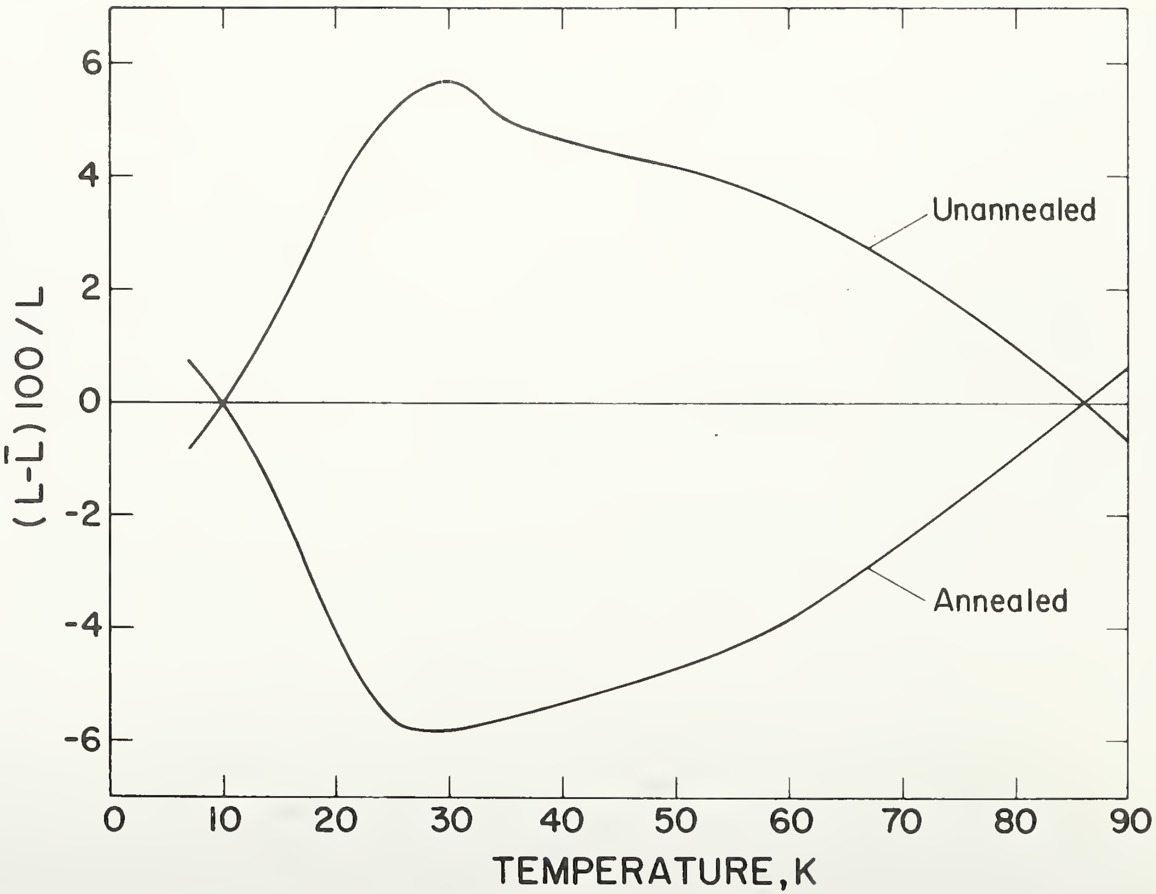

Figure 12. Lorenz ratio difference between annealed and unannealed specimens

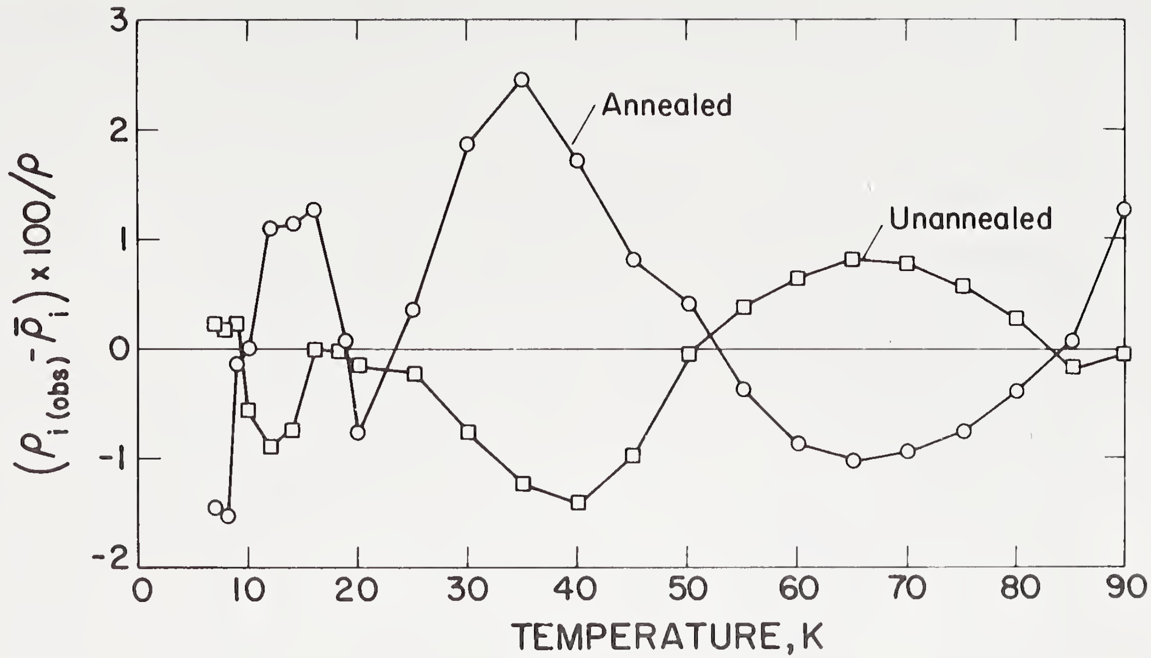

Figure 13. Deviations of intrinsic resistivities (Matthiessen's rule deviations) as computed from data for annealed and unannealed tungsten specimens.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

Thermal conductivity, electrical resistivity, Lorenz ratio, and thermopower data are reported for two specimens of NBS sintered tungsten for temperatures from 6 to 280K. Variability of this tungsten was studied by means of electrical resistivity and residual resistivity measurements on 39 specimens. These data indicate a material variability of about ±10% in thermal conductivity at helium temperatures. Above 90K variation in thermal conductivity is only about ±1%. To reduce the uncertainty caused by specimen variation at low temperatures, characterization by residual electrical resistivity data is described. By this procedure the low temperature uncertainty is reduced to about ±3%.

17. KEY WORDS (Alphabetical order, separated by semicolons)
Cryogenics; electrical resistivity;Lorenz ratio; Seebeck effect; standard reference material; thermal conductivity; transport properties; tungsten.

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